Effects of Heat-treatment on the Microstructure and Magnetostriction of $Fe_{81}Ga_{19}$ *

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Abstract Button ingots of polycrystalline $Fe_{81}Ga_{19}$ alloy are prepared by arc-melter, and the effects of different heat-treatments on their microstructure and magnetostriction are investigated. The specimens are annealed at 700℃, 800℃, and 900℃, and then cooled at different speeds, i.e. quenching into ice water, air cooling, or furnace cooling. The results show that specimens after different heat-treatments all exhibit single bcc structure, but the magnetostrictions vary from 34×10^{-6} to 94×10^{-6}; When the heating temperature is 800℃, good magnetostriction (88×10^{-6}) can be obtained by quenching. On the other hand, when the specimen is heated at a higher temperature (900℃), furnace cooling is a better way to get good magnetostriction (94×10^{-6}). It is speculated that the heat-treatment temperature and the crystal orientation may be two primary factors influencing the magentostriction of $Fe_{81}Ga_{19}$ alloy.

Key words magnetostriction, $Fe_{81}Ga_{19}$, heat-treatment

热处理对$Fe_{81}Ga_{19}$合金组织结构与磁致伸缩性能的影响

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摘要 采用电弧熔炼法制备了$Fe_{81}Ga_{19}$合金多晶样品,研究了不同热处理工艺对合金组织结构及磁致伸缩性能的影响。样品经过700℃、800℃和900℃保温后采用空冷、炉冷和淬火3种冷却方式。结果显示,经过不同热处理后样品的微观组织均为单相bcc结构,而磁致应变从34×10^{-6}到94×10^{-6}不等;当热处理温度为800℃时,淬火处理后可获得较好的磁致伸缩性能(88×10^{-6}),而热处理温度较高(900℃)时,采用炉冷的方式可获得较好的磁致伸缩性能(94×10^{-6})。推测热处理方式和晶体取向对$Fe_{81}Ga_{19}$合金磁致伸缩性能有较重要的影响。

关键词 磁致伸缩 $Fe_{81}Ga_{19}$ 热处理

Magnetostrictive materials exhibit reversible strains in the presence of magnetic field[1]. They are used to make various actuators and sensors. Current applications of magnetostrictive materials include ultrasonic cleaners, high force linear motors, positioners for adaptive optics, medical and industrial ultrasonics, pumps, and sonar etc. The giant magnetostirctive alloy $Tb_xDy_{1-x}Fe_2$ (Terfenol-D) exhibits about 2000×10^{-6} in a field of 2kOe (160kA/m) at room temperature and it is the most frequently used giant magnetostrictive materials. However, Terfenol-D alloys are brittle, require large magnetic fields for saturation, and are expensive [2].

FeGa, as a new kind of magnetostrictive materials, has attracted much attention due to its low cost, high mechanical strength, good ductility, large magnetostriction in low saturation magnetic fields, as well as negligible magnetic hysteresis[3]. Very recently, Clark et al. revealed that a magnetostriction over 200×10^{-6} is obtained at room temperature in relatively low magnetic field below 150mT in FeGa single-crystal with Ga concentration between 15at% and 25at%. All these properties implied that the FeGa alloys are promising new giant magnetostrictive materials[4-6]. At the same time, it was also been reported that the magnetostriction properties of $Fe_{72.5}Ga_{27.5}$ under furnace cooling, as-casting, directionally solidification, or quenching are different greatly, ranging from 53×10^{-6} to 114×10^{-6}. Other investigations also revealed that the magnetostrictions and microstructures of $Fe_{72.5}Ga_{27.5}$ alloy are distinctly influenced by fabricated methods and heat treatment procedures[7].

λ_{100} is the magnetostriction of FeGa alloy along the [100] crystalline direction. As showed in Fig. 1, it reaches a maximum nearly 19at% Ga and 27at% Ga at room temperature[8]. In this paper, the effects of heat-treatment procedures on the microstructure and magnetostriction of $Fe_{81}Ga_{19}$

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alloys were investigated.

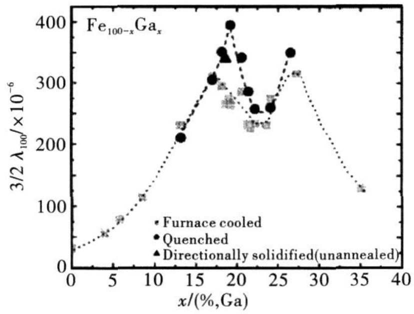

Fig. 1　(3/2) λ_{100} as a function of Ga concentration for $Fe_{100-x}Ga_x$ [2]

1　Materials and methods

Ingots of $Fe_{81}Ga_{19}$ alloy were prepared by arc melting in argon atmosphere. The purities of Fe, Ga are both 99.99%. Each specimen of the ingots, about 30g, was remelted five times to ensure homogeneity. Then the metal buttons were sealed into vacuum quartz ampoules and annealed at 700℃, 800℃ and 900℃ for 3 hours, respectively, followed by ice-water quenching, air cooling or furnace cooling. Slices were cut from the annealed buttons by a linear cutter for the investigations of the microstructure, phase structure and magnetostirction. The phase structure was identified at room temperature by a Panalytical X′ pert PRO with Cu Kα radiation. The microstructures were observed by optical microscopy. Samples for optical observation were mechanically polished and etched in a solution of 5% nitric acid + 95% ethanol[8]. The magnetostriction property was measured by standard strain gauge techniques. Strain gage was attached to the samples and the measured direction was vertical to the magnetic field, which was 0~1T.

2　Results and Discussion

Fig. 2(a) shows the backscattered electron image(BEI) of the obtained button ingot and the actual composition obtained at A, B, C spots by electron probe microanalysis (EPMA), with the results listed in Table 1. Apparently, the composition variances between different spots are very small, and the average composition of the button ingot is calculated to be $Fe_{80.84}Ga_{19.16}$, which is almost consistent with the nominal composition. The weight loss during the arc-melting is neglectably small.

Optical micrograph of $Fe_{81}Ga_{19}$ alloy after ice-water quenching from 800℃ is shown in Fig. 2(b). It can be seen that the grain sizes are about 0.1~1mm and some subgrain boundaries can be clearly observed. Similar micorstructures are also observed on the samples after other heat-treatments, either air cooling, furnace cooling or annealing at other temperatures (700℃, 900℃). It seems that the microstructure characteristics are not greatly influenced by the annealing temperatures and the subsequent cooling speed.

Table 1　Actual composition of the obtained button ingot

	Average		Point A		Point B		Point C	
Element	wt%	at%	wt%	at%	wt%	at%	wt%	at%
Fe	77.16	80.84	77.21	80.88	77.21	80.88	77.07	80.76
Ga	22.84	19.16	22.79	19.12	22.79	19.12	22.93	19.24

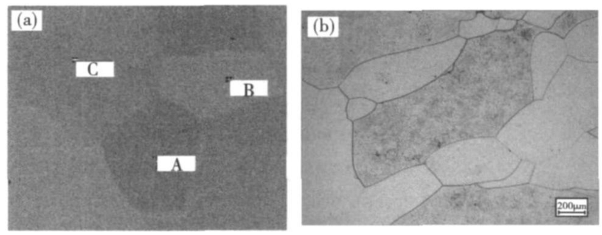

Fig. 2　BEI image of the obtained button ingot(a) and optical micrograph of $Fe_{81}Ga_{19}$ alloy after quenching from 800℃(b)

X-ray diffraction patterns of $Fe_{81}Ga_{19}$ alloy annealed at 800℃ are illustrated in Fig. 3(a). There are three peaks, which belong to A2 structure, and no peaks of $D0_3$, B2, $D0_{19}$ and $L1_2$ structures exhibit. Similar cases occur when the annealing temperature is 900℃, as shown in Fig. 3(b). It indicates that the specimens after different heat-treatments all exhibit single bcc phase. However, one noteworthy point is that the diffractive intensity of peak (211) after furnace cooling from 900℃ is much higher. The possible reasons may be two aspects, one is the cutting direction while preparing specimen accidentally favors (211) direction, another one may be that the furnace cooling is an easy manner to form (211)-preferred orientation while cooling from 900℃. As the orientated structure of FeGa has an important effect on the magnetostriction. This (211)-preferred orientation may influence the magnetostriction of $Fe_{81}Ga_{19}$ alloy.

Magnetostriction of $Fe_{81}Ga_{19}$ alloy after different heat-treatment procedures at 900℃ are showed in Fig. 4, and the saturation magnetostrictions of $Fe_{81}Ga_{19}$ alloy with different annealing temperatures are showed in Fig. 5. The obtained saturation magnetostrictions vary from 34×10^{-6} to 94×10^{-6}. It seems that the saturation magnetostrictions did not change significantly with the cooling speed when the sample was heat-treated at 700℃. Whereas, annealing at higher temperature, such as 900℃, the saturation magnetostriction became more sensitive to the cooling speed. This phenomenon may be related to the Curie temperature of FeGa alloy, which is about 720℃. When the annealing temperature is 800℃, good magnetostriction could be obtained by quenching. This is consistent with the results of A. E. Clark et al[9]. On the other hand, in our experiments, furnace cooling is a better way to get good magnetostriction when the annealing temperature is 900℃.

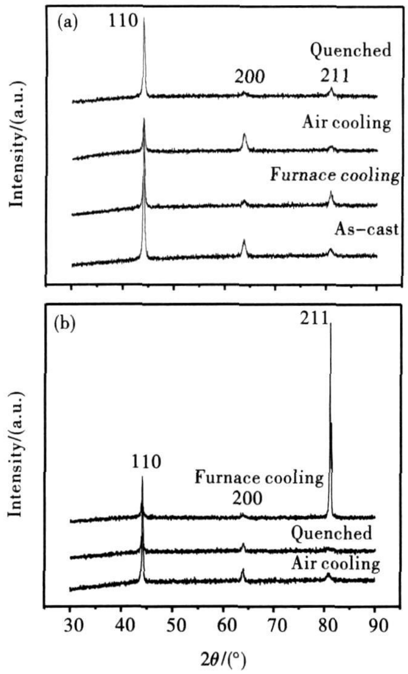

Fig. 3 X-ray diffraction patterns of $Fe_{81}Ga_{19}$ alloy after annealing at 800℃

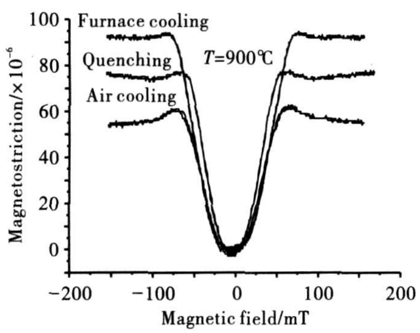

Fig. 4 Magnetostrictions of annealed $Fe_{81}Ga_{19}$ at 900℃

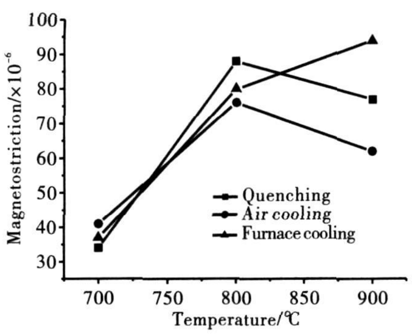

Fig. 5 Magnetostrictions versus annealing temperatures for $Fe_{81}Ga_{19}$ alloy

Table 2 listed the saturation magnetostrictions and the needed magnetic fields of $Fe_{81}Ga_{19}$ alloy. The best magnetostriction value (94×10^{-6}) is obtained after $Fe_{81}Ga_{19}$ alloy was furnace cooled after annealed at 900℃. The needed magnetic field is relatively low (75mT). From the previous results, furnace cooling from 900℃ is the only sample with highly (211) orientation. It could be speculated that the existence of (200) orientation may be the main reason of its good magnetostriction property. More investigations on this issue should be needed.

Table 2 Magnetostrictions and saturation magnetic fields of annealed $Fe_{81}Ga_{19}$ alloy

Temperature ℃	Quenching $\times10^{-6}$/mT	Air cooling $\times10^{-6}$/mT	Furnace cooling $\times10^{-6}$/mT	As-cast $\times10^{-6}$/mT
700	34/110	41/120	37/120	58/140
800	88/140	76/160	80/350	58/140
900	77/60	62/65	94/75	58/140

3 Conclusions

(1) $Fe_{81}Ga_{19}$ alloys after different heat-treatments all exhibit single bcc structure.

(2) Magnetostriction properties of $Fe_{81}Ga_{19}$ alloy become more sensitive to the cooling speed when annealed at higher temperature.

(3) The best magnetostriction value (94×10^{-6}) of $Fe_{81}Ga_{19}$ alloy is obtained by furnace cooling when the annealing temperature is 900℃. The needed magnetic field is relatively low (75mT).

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